

IN-20-2R
205066
38P

Assessment of Impact Damage of Composite Rocket Motor Cases

Final Report

by

**Dr. Henry G. Paris, Principal Research Scientist and Director
Materials Science and Technology Branch
Electro-Optics, Environment and Materials Laboratory
Georgia Tech Research Institute
Georgia Institute of Technology
Atlanta, GA 30332**

February 19, 1994

for

**Period November 1, 1993 to February 28, 1994
NASA contract NAG-1016
Marshall Space Flight Center
Huntsville, AL**

(NASA-CR-195143) ASSESSMENT OF
IMPACT DAMAGE OF COMPOSITE ROCKET
MOTOR CASES Final Report, 1 Nov.
1993 - 28 Feb. 1994 (Georgia Inst.
of Tech.) 38 p

N94-24595

Unclass

G3/20 0205066

Assessment of Impact Damage of Composite Rocket Motor Cases

Final Report

by

**Dr. Henry G. Paris, Principal Research Scientist and Director
Materials Science and Technology Branch
Electro-Optics, Environment and Materials Laboratory
Georgia Tech Research Institute
Georgia Institute of Technology
Atlanta, GA 30332**

February 19, 1994

for

**Period November 1, 1993 to February 28, 1994
NASA contract NAG-1016
Marshall Space Flight Center
Huntsville, AL**

TABLE OF CONTENTS

I.	Abstract	Page	3
II.	Statement of the Problem	Page	4
III.	Approach	Page	5
IV.	Review of Design Criteria for FWC Motor Cases	Page	5
V.	The Mechanisms of Impact Damage	Page	6
VI.	Effective NDE Methods to Quantify Damage	Page	8
VII.	The Critical Coupon Level Tests and Scaling	Page	15
VIII.	Manufacturing and Material Process Variables	Page	19
IX .	Empirical and Analytical Modeling of Damage	Page	21
X.	Summary and Recommendations	Page	25
XI.	Bibliography	Page	28

Assessment of Impact Damage of Composite Rocket Motor Cases

I. ABSTRACT

This contract reviewed the available literature on mechanisms of low velocity impact damage in filament wound rocket motor cases, NDE methods to quantify damage, critical coupon level test methods, manufacturing and material process variables and empirical and analytical modeling of impact damage. The critical design properties for rocket motor cases are biaxial hoop and axial tensile strength. Low velocity impact damage is insidious because it can create serious non-visible damage at very low impact velocities. In thick rocket motor cases the prevalent low velocity impact damage is fiber fracture and matrix cracking adjacent to the front face. In contrast, low velocity loading of thin wall cylinders induces flexure, depending on span length and the flexure induces delamination and tensile cracking on the back face wall opposed to impact. occurs due to flexural stresses imposed by impact loading. Important NDE methods for rocket motor cases are non-contacting methods that allow inspection from one side. Among these are vibrothermography, and pulse-echo methods based on acoustic-ultrasonic methods. High resolution techniques such as x-ray computed tomography appear to have merit for accurate geometrical characterization of local damage to support development of analytical models of micromechanics. The challenge of coupon level testing is to reproduce the biaxial stress state that the full scale article experiences, and to determine how to scale the composite structure to model full sized behavior. Biaxial tensile testing has been performed by uniaxially tensile loading internally pressurized cylinders. This is experimentally difficult due to gripping problems and pressure containment. Much prior work focused on uniaxial tensile testing of model filament wound cylinders. Interpretation of the results of some studies is complicated by the fact that the fabrication process did not duplicate full scale manufacturing. It is difficult to scale results from testing subscale cylinders since there are significant differences in out time of the resins relative to full scale cylinder fabrication, differences in hoop fiber tensioning and unsatisfactory coupon configurations. It appears that development of a new test method for subscale cylinders is merited. Damage tolerance may be improved by material optimization that uses fiber treatments and matrix modifications to control the fiber matrix interface bonding. It is difficult to develop process optimization in subscale cylinders without also modeling the longer out times resins experience in full scale testing. A major breakthrough in characterizing the effect of impact damage on residual strength, and understanding how to scale results of subscale evaluations, will be a sound micromechanical model that described progressive failure of the composite. Such models will utilize a three dimensional stress analysis due to the complex nature of low velocity impact stresses in thick composites. When these models are coupled with non-contact NDE methods that geometrically characterize the damage and acoustic methods that characterize the effective local elastic properties, accurate assessment of residual strength from impact damage may be possible. Directions for further development are suggested.

Assessment of Impact Damage of Composite Rocket Motor Cases

II. STATEMENT OF THE PROBLEM

Organic matrix composites are important lightweight, structural materials for advanced launch vehicles and composite rocket motor case applications. The ALS (Advanced Launch System) Program has shown that composite manufacturing technologies of filament winding and broad good dispensing can reduce weight and cost for this application.¹ Composite structures are a new design approach for rocket structures. Particularly in the case of massive booster cases careful understanding of the consequence of damage from environmental effects, incidental damage during pre-launch preparation (hail, lightening, birds, tool drop, ice) as well as from handling after manufacture and in prelaunch is demanded.

Unlike metal structures, dropped tools, runway debris, hail and ground handling can cause significant undetectable (non-visible) damage of local delaminations, matrix cracks and broken fibers that greatly reduce load bearing capability of a structural composite. This is a critical problem for the development of a certification methodology for fighter aircraft hybrid structures.² The use of full scale testing can be insufficient to certify the structure because most composites are sensitive to environmental moisture and UV effects that causes large scatter(variability) in data compared to metallic structures. **Detection of damage and prediction of strength loss from expected damage are critical design considerations. The validity of existing design methods, NDE methods and qualification test methods based upon beams and plates to composite vessels subjected to biaxial and impact loading with and without backing support is an important issue for a sound design methodology of composite rocket motor cases.**

Objective

The objective of this review is to assess in Government contractor reports and other technical literature the available information on impact damage, nondestructive identification of damage, scalability of coupon to full scale testing, analytical modeling of damage and failure, manufacturing/materials optimization and certification criteria for composite motor cases to provide recommendations for further actions.

Background

Important technical issues concerning impact damage to composite rocket motor cases deal with assessing damage and relating it to structural integrity to form a design methodology for impact damage.^{3,4} Five key areas are:

- the mechanisms of impact damage to rocket motor cases(empty and filled).
- the effective NDE methods that can quantify damage in full scale structures.
- the critical coupon level tests whose results can be scaled to full scale structures.
- the relationship of manufacturing process variables to impact damage tolerance.
- Analytical modeling of damage for a damage tolerance design philosophy.

III. APPROACH

The review of literature in this final report summarizes the information that has been identified on these five subject areas. The review was conducted through on-line searches of the ENGI, the Engineering Index, which covers the period January 1985 to February 1994, and NTIS, the National Technical Information Service database that covers the period 1964 to February 1994, as well as the Library of Congress and Georgia Tech catalogues which contained extensive Government reports. A key word package was developed for this search. In this discussion the key words are denoted by **bold face type**. Initially searches were conducted on (1) **non-destructive inspection and composites**; (2) **motor and case and composites**; (3) **damage and sensitive and composites**; (4) **Air Force and Impact and Composites**; (5) **NASA Technical Memorandum and Composites**. Additionally, author names were used as search indices when possible. Abstracts of cited articles were downloaded and reviewed. Important citations were identified based on abstract content and in most cases, full copies of the citation obtained and reviewed. This review resulted in the further identification of supporting reference citation in the articles themselves. In some cases these supporting citations have been obtained, in others only the abstracts were obtained from the on-line databases, and in others they have been simply mentioned in this review. An attempt has been made to place as many of these citations in the Procite™ software database package for reference use.

The initial assessment used in the proposal for this work identified about 160 citations in technical literature on NDI, composite motor cases and damage tolerance in composites. This list was expanded by subsequent searches to over 300, including citations contained in the search literature. The abstracts were read and culled and, although the body of relevant literature contained in the citation index is about 250-300, only about 100 or so of the particularly relevant citations are discussed in detail in the report.

IV. REVIEW OF DESIGN CRITERIA FOR FWC MOTOR CASES

The design of rocket motor cases relies primarily on the fact that rocker motor cases are subjected to internal pressurization from the ignition of the propellant, and axial tension and/or bending moments from launch loading. The internal pressurization places primary emphasis on hoop and axial tensile strength, which are a fiber dominated properties, and bending stiffness. In the initial fraction of a second while the shuttle is still locked to the launch pad, the engine thrust reaches the total weight of the Shuttle. The pressurization of the rocket motor case creates large hoop tensile stress while the mechanical constraint of the shuttle causes significant forward axial extension that is resolved as axial tensile stress in the case.⁵ The presence of bending moments enhances the potential for buckling failure due to damage at an impact site. Primarily the rocket motor case is designed to withstand the tensile stresses arising from internal pressurization.⁶⁻⁹ Early work concentrated on designs and fabrication practices using Kevlar™ reinforced HBRF-55A epoxy resin¹⁰ however, subsequently⁵⁻⁹ the higher modulus AS4 graphite fiber was selected. The effect of impact damage then must be assessed primarily on its degradation of hoop and axial tensile strength under biaxial loading.

V. THE MECHANISMS OF IMPACT DAMAGE

Effective design methodology requires understanding the actual mechanisms of impact damage in the specific structural component. Such understanding forms a basis for computational modeling of the damage and subsequent life prediction. One may expect significant differences in behavior between the impact effects on plates, hollow shells and shells with backing (propellant or structure).¹¹⁻¹⁴ That is, the resistance to impact damage of a rocket motor case loaded with propellant may be markedly different than that of an unloaded one. Flexure of the case may be restrained in filled cases and reflection of stress waves at the inner case surface may change. Yener, et. al.¹³ maintains it is possible to quantitatively assess impact damage in composite pressure vessels. This should allow insight into basic failure mechanisms. Cantwell and Morton provide two good reviews of impact resistance and mechanism of damage in composites.^{15,16}

Low Velocity Impact Damage

Low velocity impact damage is insidious because significant internal(sub-surface) damage may occur while no visible impact damage (VID) is present.¹⁷ The characterization of low velocity impact damage indicates that the primary result of impact damage in filament wound cases is fiber breakage and matrix cracking. While many investigations refer to the damage from low velocity impact as "delaminations", the destructive evaluation of laminates of both conventional lay-ups and filament wound cylinders show that damage occurs as fiber breakage and matrix resin cracking. "Delamination" appears to be observed primarily in 2-D lay-ups and in thin shells, especially unbacked, where flexural extension of the wall occurs on impact creating additional shear and transverse loading and tensile stresses on the back surface.

An extensive assessment of impact damage in rocket motor cases has been conducted by Poe.^{6,18-20} Poe evaluated thick(nom. 1.4 inch) filament wound composite rocket motor cases fabricated from graphite reinforced epoxy (AS4W graphite/HBRF-55A epoxy). The radius of the full scale case is large relative to the thickness of the wall, the case can still be considered to behave as a membrane for first order analysis; however, local effects in low velocity impact damage will still be influenced by the large section thickness. In studies of both full scale and subscale cylinders with the same wall thickness, Poe examined the effects of blunt and sharp indenters (corners, various radius hemispheres and small diameter cylinders) by both non destructive and destructive inspection. These studies also considered the effects of empty and filled shells. Poe found that conventional radiography did not indicate the presence of damage when no visible surface damage was observed. In fact, Poe notes that radiography never showed the full extent of impact damage.

The subscale cylinders used by Poe were fabricated in a different way than the full scale case. Since hoop tensile strength of the full scale case was of interest, the filament winding of subscale cases was rotated 90 degrees so the conventional hoop direction became the axial direction. This allowed relatively flat tensile coupons to test the "hoop" tensile strength. This modification means unidirectional tapes had to be used for the axial fibers since they could not be wound in the filament winding equipment. Because of the use of tapes and non-standard winding technique,

wrinkles were produced in some of the cylinder wall plies that would not be present in conventional filament wound cases. Some of this wrinkling may have resulted since the taped were not tensioned as is done in normal hoop winding.

Poe observes that the primary damage is broken fibers and matrix cracking in plies below the surface. The primary damage from low velocity impacts appears to be Hertzian cracking of fibers with patterns of broken fibers demonstrating a "crack front" normal to the fiber direction.¹⁷ Careful SEM of deplied samples showed the fiber fracture is a shear fracture. The pattern of matrix cracking was noted to be somewhat influenced by the adjacent fiber layers (axial vs. helical). This series of work also noted that impact damage was more severe for larger diameter indenters. In some cases matrix cracks within a layer did not always follow the orientation of fiber in the layer when the adjacent layers were not of parallel orientation. In these cases the crack meandered between the orientations of fiber in adjacent layers. Actual delaminations are observed only after tensile testing to failure. For most impact damage specimen, on subsequent loading failure occurred progressively with the damaged ligaments failing first and the undamaged ligaments failing subsequently at higher loads. The progressive failure of the damaged ligaments caused the failed ligaments to delaminate from the unbroken ligaments.

The observation by deply methods that the actual damage consists of matrix cracking and fiber fracture is notable. Several studies on impact damage in 2-D composites note the observation of direct delaminations.²¹⁻²⁴ Poe's work clearly suggests the phenomenon of delamination in filament wound cases may be distinctly different than in fabric composites. Poe noted that delamination was always observed as a post-failure mechanism. Fractographic and deply examination showed the delamination did not follow the interface between layers of windings but meandered within the ply. In fabric delamination, the phenomenon is almost always associated macroscopically with interply failure. This can be understood if the fabric ply presents a clear transverse discontinuity to the propagating stress impulse. Although the differentiation between matrix cracking and delamination becomes shaded at higher impact energies, Cantwell and Morton reported in their review that some researchers observe an increasing tendency for delamination as the cross ply angle increases for high velocity impacts.¹⁵

Palozotto, et al., used both C-scan and optical examination of impact damaged graphite/epoxy (AS4/3501-6) layups.²⁴ These investigators determined that the nature of damage was transverse cracking within plies, and delaminations between plies where stiffness parameters discontinuously changed. These investigators, however, also conclude that fiber **damage** occurred at impact energies as low as 2 ft-lb. in 12 ply laminates and at 4-5 ft-lb. in 24 ply laminates. These authors also conclude that fiber fracture occurs only at much higher impact energies. Bai and Harding observed the nature of impact damage in single and multiple ply glass reinforced plastic subjected to very high impact velocities in a split Hopkinson's bar test.²⁵ These investigators also observed fiber shear failure followed by matrix yielding. The nature of impact damage from low velocity impact in filament wound composite cylinders can be concluded to be fiber fracture and matrix cracking transverse to the fiber direction.

On the basis of this latter observation, it can be suggested that the significant difference between the impact damage observed by Poe in filament wound, or simulated filament wound composites and in 2-D laminates by other investigators is that absence of distinct interfaces between orientations in the filament wound case. This may prevent large delaminations between ply orientations compared to 2-D composites. Poe's observation of delamination as a post-loading phenomena is consistent with the progressive ligament failure mechanism he observed. Upon failure of a damaged ligament, the ligament delaminates from the unbroken ligament by the stresses generated in unloading the failed ligament. The fact that Poe evaluated relatively thick composites also may be significant as thicker sections exhibit less flexure on impact. Furthermore, tensile testing thick composite coupons is difficult. It is impossible to achieve effective transfer of the tensile load from the grip ends into the tensile coupon (shear lag) in a reasonable distance. As a consequence, it is difficult to determine if this load transfer problem is an influence in the ligament failures Poe observed.

This relationship of the nature of damage to laminate micro-configuration makes the wide use of artificial damage techniques^{22,23,26} suspect for interpreting the effects of impact damage in filament wound structures and for very low impact energies in 2-D laminates. These methods create actual disbonds in the plane of the composite while experimental observations show the primary damage in low velocity impact is fiber fracture by shear and transverse matrix cracks normal to the fibers.

Of equal importance is Poe's observation that pressure testing of quarter scale vessels did not exhibit a two stage ligament failure. He observes that the thin wall cylinders may display less damage than thick wall cylinders. This suggests that fracture may be sensitive to the magnitude of the damage size, suggesting classical energetic models based fracture mechanics phenomena may be useful.

VI. EFFECTIVE NDE METHODS TO QUANTIFY DAMAGE

NDE methods address two distinct needs; (1) polling the damaged material to determine local elastic stiffness; and (2) quantification and detection of actual physical damage. In order to use computational methods to correlate quantified damage for life prediction, to model failure mechanisms and to support design methods, such damage first must be measurable in both coupon and full scale components. Quantifying the reduction in life or load carrying capability of a large structure due to incidental damage is essential since a design philosophy that is based on worst case criteria (preventing damage) may yield prohibitive manufacturing cost/complexity and excessive structural weight. Furthermore, even if a computational methodology for predicting structural integrity after impact is available, in service one cannot usually effectively quantify the energy or force of impact except under unusual or controlled circumstances. NDE methods are critically important. Cantwell and Morton review many of the NDE methods for detection of defects in composites.²⁷

NDE of large structures with re-entrant or closed surfaces such as filled pressure vessels is difficult. Ultrasonic techniques such as C-scan require large fixtures and usually access to both sides of a structure. Other NDE methods are available. Some of these are X-ray tomography, thermography, radiography, laser-interferometry coupled with acoustic methods, and for graphite reinforced composites, eddy current and and/or magnetic field mapping methods.²⁸⁻³⁰ Many of these methods are still "developmental." Although ultrasonic methods are widely used, other NDE method may offer improved damage assessment. Such methods are critical to quantifying the extent of damage and to build an empirical understanding of the relationship between damage and test coupon results.

Because of the ubiquitous presence of foreign object damage (FOD), the Air Force has placed substantial effort into identifying and characterizing impact damage in composite aircraft and missile structures. Cordell and Bhagat³¹ have carefully summarized the current status of the Air Force program in NDE. Cordell notes that observed variability in composite performance has pushed the materials developers towards compositional controls and the use of improved tougher resin systems to improve the resistance to impact damage. This trend towards improved resins presents the NDE inspection process with a dilemma, as the resins become tougher to provide improved damage tolerance, the impact damage that does occur becomes more localized and difficult to detect. The major objectives of the Air Force NDE program are to identify delaminations and measure performance degradation due to damage. Traditional NDE methods, as noted by Poe,^{6,18-20} are inadequate to provide the necessary resolution to define the extent of damage in composites. Poe¹⁸ noted that radiography did not reveal nonvisible damage in 1.4 inch thick scaled cylinders when impacted by 0.5 inch radius impactor.

Acousto-ultrasonics

Vary and Kautz^{30,32,33} present extensive review of the acousto-ultrasonic approach. This method is similar to acoustic emission techniques where a structure is loaded and the structure monitored by transducers. "Events" such as breaking fibers, matrix cracking, delaminations produce ultrasonic signals as the strain energy associated with the event(s) is released. The problem with acoustic emission is that there is no clear spatial location for "events" and it is difficult to correlate specific types of damage in complex structures with specific acoustic emission events.

As Vary notes, acousto-ultrasonic (AU) techniques offer two direct advantages. First it can be a single side sampling method. Second, acousto-ultrasonics attempt to surmount the problem of ill-defined correlation of acoustic emission with specific defect types by exciting a specific stress wave via some impulse and monitoring its reflection by elements of the structure such as existing damage. Since the propagation of sound(stress waves) in a structure is fundamentally related to a elastic properties, it is possible to use this technique to sample the elastic stiffness of the composite. In principle this ultrasonically measured local stiffness can be used in analytical models based on initial fiber and composite properties to predict degradation in strength/stiffness from damage. This method differs from pulse-echo methods where suitable signal processing can be used to spatially correlate reflected stress waves in the structure with

defects and to identify defect location. The acousto-ultrasonic technique primarily is a method to assess the integrated effects of local damage on structural response(stiffness, strength), not to define specific damage locations.

Kautz^{34,35} has applied acousto-ultrasonic waveform partitioning to the NDE of filament wound composite specimen. The AU analyses were compared to destructively obtained interlaminar shear strength (ISS) and the obtained AU stress wave factors(SWF) were regressed against the ISS yielding better than a 90% correlation factor. There is indication in this work that the technique is sensitive to changes in depth within the specimen.

A major experimental difficulty with AU is the need to couple the acoustic signal to the structure either by immersion in a fluid, the use of oil, grease or other coupling media. The use of a low power laser to excite stress waves is developed to surmount this problem. Even so, coupling can be a problem. The presence of surface roughness and contamination can change reflectivity and emissivity which changes the energy transfer to the structure.³²

Ultrasonic Testing

Ultrasonic testing is based on the principle that a propagating sound wave is attenuated or reflected by discontinuities in mass density. Such discontinuities, depending on wavelength, can be porosity, delaminations, matrix cracks and fiber breaks. Composites are inherently discontinuous structures therefore resolution of acoustic scattering from discrete damage will strongly depend on the background "noise" level of acoustic scattering from the inherent structural anisotropy of the composite. Generally, higher frequencies provide better spatial resolution but the attenuation of acoustic scattering by intrinsic heterogeneity increases with frequency. The use of UT for composite inspection presents a continuing trade between spatial resolution(frequency) and signal detection(attenuation). Backscatter methods require the gating of the signal to resolve front and back face reflections. This reduces the resolution of the technique in near surface regions. Tardiff and Taber recently reported the difficulty of ultrasonic inspection of filament wound graphite epoxy cylinders.³⁶ They were limited to inspection of about 70% of the total thickness using pulse-echo C-scans due to the need to gate the signal. The advent of fast low cost computers for signal processing can ameliorate this problem by eliminating the prior demands on gating with the use of synthetic apertures. When the signal is not gated, the entire wave form can be analyzed. This allows better resolution of the volume near the front face. Signal processing is a principal advance by connecting acoustic and ultrasonic quantitative methods.

Acoustic microscopy

Acoustic microscopy(AM) is used for near surface inspection of relatively homogeneous materials. Imaging of defects in homogeneous materials is easily done. Some workers have explored its use in composite structures. Several barriers must be surmounted. Available commercial AM tools are insensitive to directional influenced properties that arise from the anisotropy of composites. The frequencies are high and significant attenuation also occurs. Awal

and Kundu³⁷ have attempted to modify the acoustic microscope to inspect composites. They have followed others in the acousto-ultrasonic methodology in changing the spherical lens to a line focus lens and used lower frequencies (0.5 to 2.5 MHz). This allows directional analysis. By orienting the linear source normal to the principal fiber direction in a ply, they may analyze each ply layer. They have observed signals in impact damaged single ply and 11 ply 0/90 layups of uni-directional tapes. Although the presence of damage was observed in both type of composites, to date these workers have only demonstrated that a suitably modified acoustic microscope is sensitive to directionally dependent properties in anisotropic composites. This technique appears to require significant additional work.

Pulse-Echo/Backscatter Ultrasonic Techniques

For inspection of filament wound vessels, a one side ultrasonic examination method is essential. A number of variations on backscatter, or reflection techniques were found. Steiner³⁸ summarizes work done at the University of Delaware. These workers have focused primarily on backscatter and through transmission C-scan methods with advanced signal processing to determine time of flight. The disadvantage of backscatter methods is the signal must traverse the thickness twice while a through-thickness transmitted signal must traverse it once. Additionally, the methods used by this group require robotics and immersion for coupling ultrasonic signals. Although frequencies of 15-25 MHz are used which should allow spatial resolution of 0.05 to 0.075 mm (50 to 75 micrometers), the mechanical errors of the robotics limit resolution to about 0.1mm (100 micrometers). Suitable signal gating demonstrates impressive imaging capability of delaminations resulting from low speed impact damage in AS4/3501-6 graphite-epoxy system. The method appears limited for application to rocket motor cases since immersion and robotics are required. It could be quite useful for evaluating sub-scale cases. A significant advance demonstrated by this work and others is the use of spectral analysis techniques to enhance the amount of information developed in the inspection.

Numerous workers are implementing advances in the area of modification of ultrasonic backscatter inspection techniques coupled with signal processing methods.³⁹⁻⁴⁵ The primary advances in ultrasonic methods relevant to inspection of impact damage of filament wound rocket motor cases is the use of non-contact, locally excited, acoustic impulses by laser,³⁹ and spectral density analysis such as used by Burger.^{44,45}

Morton Thiokol reported the use of acoustic emission and pulse echo techniques for inspection of the SRB filament wound case.⁴⁶ Post test inspection showed depth measurements of defects were not accurate beyond about 0.26 inches and pulse echo measurements exceeded actual part thickness by 10 to 14%. Delaminations could be mapped within the accuracy of the equipment. The basic challenge for these techniques applied to filament wound rocket motor cases is assessed by Thompson, et al.⁴² The methods must couple analytical models of anisotropic elastic constants with the measured directional acoustic signals in order obtain spatial information from the detected backscattered C-scan signals. Spatial definition must be on the order of the critical length scale for analytical micromechanical modeling.

Besides their use in image analysis, such information on elastic constants can be used in analytical models such as those developed by Greszczuk⁴⁷ to model buckling behavior. After the elastic constants are determined, synthetic aperture techniques can be used to modify the B-scan to produce flaw imagery. Thompson, et al, used artificial defects (minimum size 0.125 in diameter) placed in 1 inch thick Plexiglas and graphite/epoxy. Both B-scan and synthetic aperture focused technique(SAFT) imagery provided approximately 1% error in depth resolution. The spatial resolution of B-scan was poor but that of the SAFT of the 0.125 in diameter defects still had 5% error. Minimum flaw size detectability was not noted in this work, but it can be inferred on the basis of the 5% error in dimension to be no better than about 0.2-.4 mm, or 200-400 micrometers, at best.

Andrews and Martin⁴³ also applied signal processing methods to A-, B- and C-scan backscatter image data. Using a 25 MHz signal frequency, they demonstrated ply by ply resolution of matrix cracking a [0/90/+60]_S graphite/epoxy laminate. Resolution is estimated from the micrographs presented in the work to be approximately 0.5 mm(500 micrometer). The specific method would not be usable for full scale inspection since immersion would seem to be required for signal coupling.

Yost and Cantrell⁴⁸ also have evaluated a method for launching bulk in-plane acoustic waves in a composite. This method is a single sided technique but it requires direct coupling of the acoustic signal to the laminate by direct contact. In this case they placed on the composite surface a Lucite block with the transducer bonded to it. While suitable signal processing methods can be used, the method is limited because it requires contact with the composite surface similar to that proposed by Burger.^{40,41}

Non-contact Ultrasonic Methods

To achieve the scale of resolution demonstrated in the previous references in large composite structures one must eliminate the effects of surface roughness and the need for immersion for conventional ultrasonic inspection. Burger describes such a methodology in detail, called Thermo-Acoustic Photonic NDE^{44,45}. Several useful citations on prior supporting work are noted in these references. Ultrasonic sampling methods coupled with high speed signal processing appear to have resolution capability approaching a few tenths of a millimeter(hundreds of micrometers). The use of non-contact pulse echo methods coupled with synthetic aperture techniques significantly improves the capability of the previous methods.

A thermographic imaging method called vibrothermography relies the application of mechanical vibration and the generation of heat due to the free vibration of damaged elements in the vicinity of a flaw.⁴⁹ Research has shown that flaws, specifically delaminations, modify the higher natural frequencies of vibration of composite plates. The phenomena can be studied using finite element methods. The local damage shows a coupled behavior, appearing to vibrate in phase with the structure at low frequencies then passing through a critical higher frequency in which it vibrates out of phase resulting in energy loss which appears in the form of heat.⁵⁰ By using very high resolution thermographic cameras, these very small increases in local temperature

generated by a surface excited vibration can be observed. High resolution images can be converted to a false color scale revealing the subsurface defects that caused the subsurface heating. Tenek and Henneke call the technique SPATE, and have shown that the relative location of artificial damage(disbonds) can be defined using this technique. The technique is robust, it can be applied to large structures. It is possible to utilize sophisticated, high resolution thermographic cameras to scan relatively large areas of a structure excited by external vibration to define localized damaged areas. If higher spatial resolution is desired, after the damaged area is defined by the SPATE method, other higher resolution techniques can be used to quantify the damage. This method is attractive since it requires minimal surface preparation and is relatively rapid to allow large structure examination. Since it is based on flaw dynamics, it may be possible to define an approximate damage extent by using knowledge of the resonant frequencies, heat generated and finite element models of the phenomena. This approach seems highly attractive for a surveying large surface areas to identify the presence and location of damage that may be more fully characterized by NDE tools with higher spatial resolution.

Careful analysis of digitized video images of composites damaged by impact can be used to define the lateral extent of damage in the composite if the surface first has visually resolved grids on it.⁵¹ These workers examined glass reinforced epoxy transversely reinforced by stitching. Although the methodology used in this work is difficult to clearly define due to the poor English and lack of clear description of experimental procedure, it appears the investigators were able to correlate changes in surface profile over an impact damage area with degree of matrix cracking. The surface grid pattern of the stitching and a high resolution video camera provide periodic imaging cues for interferometry. Delamination, matrix cracking, fiber cracking and through thickness crushing are claimed to be differentiated. This method appears as good as vibrothermography and holographic methods.

Holographic methods were evaluated by NASA contractors in the early 1970's.⁵² This method is similar to the vibrothermography method, it relies on detecting by holographic imaging a surface strain state that is caused by an externally applied stress from heating, pressurization or acoustic vibration. This technique appears to be quite limited by theory and practice in its ability to evaluate non-planar and large surfaces.

Tomographic methods

X-ray tomography has recently been successfully applied to imaging defect structure in composites.^{31,53,54} Tomographic methods rely on the principal that x-ray absorption is a function of density of the density of material irradiated. By measuring intensity of a well collimated beam passing through an object over a wide range of solid angles, it is possible to reconstruct a density profile for the target. The technique had been widely used in medical fields and most available equipment for inspection is based on hospital use, for example the General electric CGR-ND 8000 scanner used by Bathias.⁵³ An additional complexity is that the data reduction algorithms in medical units are based on inspection of human forms and contain corrections for skeletal influences. Suitable modification of commercially available data reduction packages is necessary. The medical instruments are capable of resolving on the order of 0.1mm (100 micrometers) and

mass density differences of 10^{-3} . Bathias⁵³ showed the medical scanner can image relatively severe impact damage in 64 ply thickness T300/5208 graphite/epoxy composite.

Medical scanners also are severely limited in source brightness, therefore resolution is limited by the degree of collimating that can be applied to the source without severely reducing intensity of the beam. Specialized X-ray tomography microscopes (XTM) have been developed that use high resolution solid state detectors and high intensity monochromatic synchrotron radiation. With these advances it is possible to achieve 1-20 micrometer resolution. Recently Kinney, et al⁵⁵ showed that interfiber porosity can be measured to the resolution of a SiC fiber tow. While the use of high brightness x-ray sources requires access to synchrotrons such as described by Kinney, et al., improved industrial units are available that can achieve on the order of 25 micrometer resolution.⁵⁴ In this study the researchers demonstrated a breadboard scanner that could marginally resolve boron fibers in a boron/Al composite.

XTM has certain limits that prevent it from being used as a large structure inspection method. The sample size is small and as the sample becomes larger so does both the time to acquire data and the required storage memory for acquired data. However, the Air Force has funded work to develop a backscatter tomographic method that could be used similarly to non-contact acousto-ultrasonic methods.³⁹ Generally, tomographic methods when combined with non-contact acoustic methods allow both elastic stiffness and geometric morphology of damaged areas to be characterized. It is possible that the combination of these two methods with analytical treatments of sub scale damage in coupons could provide the basis for a sufficiently detailed physical model of impact damage to predict the degradation of impact damage monitored in full scale structures by acousto-ultrasonic methods. Such an accomplishment would have widespread applicability to composite damage tolerance design.

In summary, the use of vibrothermography, specifically SPATE, allow relatively rapid survey of large areas but do not offer high resolution for examination of local areas. Backscatter techniques based on acousto-ultrasonics(non-contact, acoustic pulse-echo methods using synthetic aperture methods) and potentially the Air Force backscatter X-ray tomography method offer the ability to carefully characterize local areas of damage identified by the previous techniques. Non contact AU methods offer the ability to poll local elastic properties. For evaluation of subscale coupons to support analytical modeling, CT methods couple with AU methods seem to offer the best opportunities. Deply methods in which the matrix is dissolved offer the best opportunity to characterize actual fiber damage in suspect areas. Radiography does not appear to be a well suited NDE method for quantitative analysis of damage, as best results utilize an infiltrated radio-opaque dye. Deply techniques offer a very good way to characterize actual fiber and delamination damage as a destructive test to support micromechanical model development.

VII. THE CRITICAL COUPON LEVEL TESTS AND SCALING

The initial exploration of literature on rocket motor cases suggested scaling of test results is problematic. For example, one researcher claims that "there is no proven scaling law for reliably predicting damage tolerance of brittle composite structures based upon the results of laboratory coupon testing"⁴⁹ In fact, it appears that in practice, verification of damage criteria and analysis methods for the NASA Fracture Control Document is based upon full scale testing of filament wound case segments (FWC)^{7,56} in the shuttle program.

Full scale testing of large structures to develop certification criteria is difficult and costly due to the wide scatter in data due to composite variability and environmental effects. It is very important to understand how one can proceed through scaling of assessed damage in subelement or coupon tests to large structures using a building block approach.² The challenge of computational methodology is to scale prediction of the life of large structures based upon test data from small coupons.

The radius of curvature of subscale cylinders prevents obtaining flat hoop oriented test coupons. These curved samples may fail in flexure and clearly the presence of bending moments is not representative of the actual stress state in service. Poe attempts to surmount this problem by reorienting the filament winding and unidirectional tapes, where the helical wound fibers now represent the old longitudinal/axial direction and the tape the now longitudinal oriented "hoop" direction.

It is important to understand that the characterization of scaling phenomena have focused in two distinct ways. One group has focused on evaluating scaling of actual critical test properties, while the other group have focused on scaling of local damage, and not necessarily relating observed damage with macroscopic property response. The latter approach is important to support analytical models that can explain the responses observed in the first approach. Both approaches must account for the significant differences in manufacturing processing from subscale to full scale components.

The NASA Industry Standard Compression After Impact Test is a historical test method for assessing impact damage. The ability to use this test by correlating energy of the impact with residual strength is an important basis for design of many composite structures. The residual compressive strength is a relevant design parameter for aircraft structural elements, for example, upper wing skins that are loaded in compression and lower wing skins that may experience strong compressive loading upon landing. The question presented in the use of such tests is whether the results from the coupon predict the response of a larger structure. Aircraft design and service experience generally shows that coupon level tests retain a lower compressive strength than larger stiffened panels.

While the NASA Compression Strength After Impact test is highly useful for aircraft structures loaded in compression, coupon tensile tests seem most appropriate for filament wound pressure vessels. The primary design strength property of the shuttle motor case is the hoop tensile strength as the vessel is loaded in hoop and axial tension. Thus a "biaxial tension strength

after Impact" test seems more appropriate. Poe^{6,18-20} discussed the critical coupon tests for filament wound composites and points out the difficulty in obtaining such data in coupon level tests.

Chen, Wu and Yeh⁵¹ present a good assessment of this scaling effects of damage and damage localization from impact on the compressive strength of flat panels and stiffened structures used in aircraft components. Two alternative explanations of this effect are that the complex larger structure offers alternative load paths to redistribute stress, or that complex structures sustain less actual damage at a given impact energy due to structural deflections. Although the authors treat the scaling effects in large structures separately, in the current work they point out that even a 100 ft-lb. impact creates damage localized to the general volume below the contact surface area of the impacting object.⁵⁷ These authors combine direct finite element analysis (FEA) with NASTRAN to treat local damage as an area with either localized elastic or stress relaxation and experimental observation to determine if stress distribution is significantly different in coupons and panels; or similar. The former observation would support structural compliance as the source of scaling effects and the latter would support the conclusion that severity of damage is the cause.

The FEA shows that stress redistribution is highly localized to the regions of 2-3 times the damage size. The authors note competing failure mechanisms may be present, elastic relaxation with high strength retention which promotes failure outside the damage zone by stress concentration; and stress relaxation with high elastic retention which promotes failure within the damage zone. Because of this competition of failure mechanisms the damage is less sensitivity to specific loss of elastic and strength properties which are position dependent. This result "is consistent with the concept of continuum damage mechanics which treats the microscopic damage as a macroscopic degradation process."⁵¹ Their FEA based on this assumption shows that the shear stiffness G_{12} is the primary factor that dominates compression after impact results. Damage severity, not stress redistribution is concluded to be the main cause of scaling.

Pressure vessels and cylinders experience significantly different loading than aircraft structures discussed by Chen, et al.⁵¹ In the latter case, care is required in the use of compression strength after impact as predictive tools for design. Swanson has addressed questions similar to Chen for the case of both composite plates and cylinders subjected to either quasi-static or dynamic loading.⁵⁸ Swanson observed in a series of related prior work that scaling of the *linear response* could be predicted over a range of specimen sizes but found scaling of *damage and failure mechanisms* a more intractable problem. Swanson provides an amplification of the statement of the problem by Chen.⁵⁹ He separates failure into a phenomena related either to stress or strain(local damage), or to energetic principles where linear elastic fracture mechanics can apply. In the latter case the absolute size of the crack is important and scaled miniature samples will fail at higher stress levels than larger ones leading to the condition of over-predicted strength after damage.

Swanson⁶⁰ attacked this problem by producing both plates and cylinders whose sizes were scaled dimensionally by factors between 1 and 5 down to the ply group level(not at the fiber or

ply thickness level). The cylinders used in Swanson's study were made by methods described elsewhere.^{61,62} Using data from over 400 plate tests and 200 cylinder tests in previous work cited in this paper, he finds that the linear response of a structure scales in time with size if both specimen and impactor are scaled geometrically. This applied for both quasi-static and dynamic events.

This study also characterized the extent of impact damage. Using C-scan and deply techniques, he quantified the area of damage and extent of broken fibers. C-scan only shows the extent of damage integrated through the thickness and defines the lateral extent of damage. Swanson showed that this delamination size did not scale with plate or cylinder size, but increased with increasing plate size. When size of delamination was compared to impact velocity, the data extrapolates to a minimum velocity to initiate "delamination." This data is consistent with an energy release mechanism based on fracture mechanics that predicts a size effect. That is, the results suggest the energy of the impact and the strain energy release determines delamination size not the applied stress or strain levels.

This study also reported the analysis of length of the broken fiber region in a ply in only the damaged plates. He observed that all the sample sizes extrapolated to the same critical impactor velocity at zero fiber length region. This result suggests that the extent of broken fibers is not size dependent (is not a fracture mechanics phenomena) but depends only on the stresses on impact.

This result is somewhat consistent with Poe,^{6,18-20} who conducted a detailed microscopic examination of fiber damage in cylinders by deply techniques. Poe, however on tensile testing coupons obtained from impact damaged filament wound cylinders only observed fiber fracture and matrix cracking and noted delaminations only after destructive tensile testing.

Swanson's result⁶⁰ suggest that fiber failure depends only on impact stress, while delamination is a fracture mechanics phenomenon that depends on the absolute crack size and will demonstrate a size scaling effect that can be quantified. Swanson's work is incomplete, as detailed tensile testing of the samples after damage would have also provided valuable information on the observed scaling laws for damage apply to actual structural response as conducted by Poe.^{6,18-20} Based on this and subsequent work, Swanson has summarized procedures for predicting damage formation and strength loss with emphasis on scaling results relative to structure size.⁶³

Some preliminary observations find that the usual basis for the test, correlation of strength to impact energy, is not effective in composite vessels, but a correlation of impact force with strength can be used.^{64,65} Sjoblom⁶⁶ has attempted to define the threshold values for damage initiation in graphite fiber reinforced plates subjected to low velocity impact. He evaluated four plate thicknesses and two resin systems reinforced with AS4 graphite fiber. A threshold velocity for damage was observed for specific materials, and the value determined from small coupon tests could be used to predict the corresponding value for plates of other thicknesses by straight-forward formulas. This work merits further evaluation, for example, how confidently can one

extrapolate to appreciably larger thicknesses, and, how does one accommodate variation in process variables in larger samples such as the case with large FWC rocket motors?

Vibrothermography as a Scaling Tool

One group of researchers⁶⁷ have treated the phenomena of thermal emission both numerically and experimentally to determine the state of surface stress for damage assessment and repair. These workers maintain that thermal emission reflects the interaction of load, geometry, material and damage in a method where it may be possible to scale test data from coupons to tests on full scale structures.

Kellas and Morton^{68,69} have evaluated factors responsible for scale effects on tensile strength in angle-ply composites. In this study they found that fiber dominated layups were less sensitive to scale effects. A significant observation was that transverse ply cracks whose extent and occurrence is sensitive to ply thickness appear to be responsible for strength and failure mode variations in different sized specimen.

O'Brien and Salpekar have examined the effect of scale on transverse tensile strength of graphite epoxy composites.⁷⁰ These workers evaluated 90 degree cross ply laminates in three widths and five thicknesses to determine the effects of the grip in tensile testing on failure locations. Their results suggest matrix dominated properties vary with volume of material stressed. Strength decreased as volume increased. Using Weibull statistics, they were able to develop a volumetric scaling law for transverse tensile strength in three point bending. The researchers discuss significance of the work on scaling to design allowables.

One unusual approach to achieving effective scaling of microscopic damage with global mechanical response is the use of characterization of damage geometry by fractal methods.⁷¹ Although the work is embryonic, it may lead to methods of characterizing the geometric extent of damage to allow effective scaling laws in micromechanical models, which can be used to predict macroscopic response to loading in the presence of microscopic damage.

In summary, scaling the effects of impact damage from subscale cylinders and test coupons to full scale behavior is very difficult. Previous work has shown it is difficult to produce composite fiber-ply geometry in subscale that is equivalent to full scale components. Significant differences are observed in subscale and full scale coupons. Furthermore, service loading is a biaxial tensile state and most work has only addressed simple tension loading. Impact damage in subscale cylinders with thin walls, while perhaps meeting the same criteria of being able to be modeled as a membrane, may experience added flexural loading that may enhance in-plane delamination. It is very difficult to obtain hoop orientation specimen that allow tensile testing without flexural loading. Alternative tensile test methods and the use of test methods with biaxial stress states is needed. As described in the next section, manufacturing details of subscale and full scale cylinders are quite different and the manufacturing differences also create significant material differences. The most fruitful approach may be to develop micromechanical models of damage in subscale elements with the hope of extending the micromechanics to describe behavior of large

scale components with different composite microstructures. The use of local damage characterization NDE tools described in the previous section would provide great support for this approach.

VIII. MANUFACTURING AND MATERIAL PROCESS VARIABLES

With a strong foundation in composite design based on quantifying damage, understanding mechanisms and computational modeling, it becomes important to understand if one can then develop the correlation to processing parameters such as resin properties, polymerization processes and fiber properties and orientation to such damage and design criteria. If this is possible, optimized process control methods to achieve maximum impact damage resistance can be developed. For example, the burst strength of filament wound composite vessels is reported to be correlated to resin matrix properties and as much as a 35% increase in burst strength can be obtained by optimization.⁶⁹

In the early stage of development of the NASA FWC Shuttle Booster program significant effort was placed into understanding and controlling resin properties and manufacturing process optimization in order to achieve a stable database of stiffness properties of the AS4-12K graphite fiber/HBRF-55A resin system. Verderai summarized this work in two NASA Technical Papers.^{5,73} Specific details of the actual fabrication program are not clearly described in the two citations however, the author alludes to many manufacturing problems in both six inch diameter bottles and full scale articles that strongly influenced stiffness of the filament wound cylinders. The elastic properties cited by Verderai could be a *starting* point for material properties for analytical models. Work by Pearce and Mijovic⁷⁴ on HBRF 55A resin provided from full scale filament wound cases showed significant material inadequacies that were supported by electron microscopic analysis. A major problem faces both scaling subscale cases and optimizing resins and processes in the fact that winding a 240 inch diameter cylinder requires extensive time relative to winding smaller sub scale coupons. Extended winding times allow loss of volatile compounds and possible chemical changes in the resin during manufacturing (curing) that add processing variables that are very difficult to simulate in subscale cylinders. Unless subscale cylinders can be manufactured using similar winding times so the resin in the subscale sees similar out times prior to curing it may be very difficult to produce test coupons with similar manufacturing induced material characteristics. Such manufacturing effects have been noticed in the fabrication of composite pressure vessels subjected to strong compressive stresses as early as 1965.⁷⁵ In this work, fabrication effects were noted to influence the state of residual stress in a glass reinforced composite cylinders.

Impact damage - effects of matrix toughness and fiber matrix interface

One question posed by this work is how does the toughness of the matrix and the fiber-matrix interface influence the type of damage. These effects are observed to apply to low velocity impacts. Several investigations have also shown that as the energy of the impact event increases, the effects of matrix properties diminishes and the observed degradation in strength of the composite converges^{6,59}

Previous Air Force sponsored work, primarily focused on compression strength after impact damage (CAI) evaluated low velocity impact in AS4/APC-2 graphite/PEEK and graphite/BMI composites.⁷⁶ The rationale for using PEEK (polyetheretherketone) rather than BMI(bismaleimide) is that it is a "tougher" resin than BMI. Although microscopic examination of specific matrix damage resulting from impact was not presented, the results of post impact compression testing showed that in thin laminates (less than 70 plies) the tougher PEEK matrix gave better results. In thinner laminates the reverse was observed. Teh and Morton⁷⁷ evaluated residual compressive strength in CAI tests for nine fiber reinforced systems. These workers observed a critical threshold impact velocity below which damage was not detected. Using C-scan techniques damage area was linearly correlated with impact velocity. Since both brittle and ductile systems were evaluated, the researchers were able to determine that matrix properties are highly important in the threshold damage regime, with the brittle matrix systems showing more damage and lower residual strength for a given impact velocity. Particularly, the workers noted that normalized compression strengths based on a given damaged area were almost identical for all systems and independent of material properties.

A similar study of the same graphite/Peek system and an AS4/3501-6 brittle epoxy matrix system in $[0/+45/-45/90]_{4S}$ 32 ply layups. This study used signal processing methods on ultrasonic inspection data to resolve the damage. This study showed, especially in the brittle epoxy system a series of localized "delaminations" in each ply. The orientation of the damage within the ply rotated with the orientation of the ply lay-up orientation. In the brittle system some continuation of damage in the same orientation as the previous ply was observed at the interface between lay-up orientation changes. The authors conclusively identify the damage in both systems as delamination; however, no de-plying examination was undertaken to determine the actual nature of the damage. It is possible that the observation of "delaminations" may be extensive matrix cracking normal to the fibers as observed in the studies of Poe. It is clear in this study that the extent of damage for similar laminate lay-up is reduced drastically by the use of the tougher PEEK matrix.

Bascom and Drzal⁷⁸ and Bascom⁷⁹ evaluated the surface properties of carbon fibers, sizing and their adhesion to various organic polymers that may offer a tougher matrix and improve impact damage. In these two studies none of the alternative polymers (polycarbonate, polyphenylene oxide, polyetherimide, polysulfone, polyphenylene oxide blends with polystyrene, and polycarbonate blends with polycarbonate polysiloxane block copolymer) yielded adhesion strengths as high as epoxies. Surface properties of carbon fibers, techniques for surface analysis, polymer/fiber bond strength measurement and fiber-matrix adhesion on composite mechanical properties were reviewed and research recommendations offered. Subsequent work by Paul and Buntin⁸⁰ attempted to achieve improved impact and fracture resistance by applying discrete elastomeric or polystyrene particles to the fiber surfaces with no success.

Dauksys⁸¹ determined in an Air Force study that the interlaminar shear strength of graphite reinforced composites could be appreciably improved by the use of chemical pretreatments of the fibers. Clear evidence of improved adhesion of resin to fibers with minimal reduction in fiber

tensile strength was observed. Unfortunately, highly toxic chemicals such as osmium tetroxide and stannic chloride are used and present difficulty scaling to in-line continuous operation.

Substantial micromechanical details remain unexplored in the literature reviewed for this report. The interfacial bonding of fiber to matrix serves several purposes. On one hand very high bonding strengths impart significant elastic constraint to the matrix by the fiber as load is readily transferred into the matrix. This enhances the likelihood of matrix cracking upon fiber fracture. A controlled interfacial bond at perhaps lower energy may allow effective load transfer (elastic constraint) but also allow local disbond rather than matrix fracture. This could reduce the propensity for propagation of extensive matrix cracking on impact damage. These would appear to be useful areas to explore. Reducing the effect of the significant long winding time of large cylinders is an area where resin optimization and/or alternative manufacturing techniques offer promise.

IX. EMPIRICAL AND ANALYTICAL MODELING OF DAMAGE

Analytical modeling of the damaged and undamaged vessels is the ultimate basis of a predictive design methodology and of scaling subscale test results to full scale structures. There appears to be some disagreement on the maturity of composite failure criteria and its use in design. Swanson⁵⁸ maintains the failure criteria for composites, and hence, the appropriate design methodology, is not well understood. In specialized munitions applications, modeling has been used in the critical design criterion for small rocket (munitions) motor cases to allow design for specific, controlled failure after impact to allow rapid venting rather than explosion.¹²

It will be useful to determine whether a sound analytical basis for treating the problem of coupon testing and composite design of motor cases for impact resistance is available and whether such analysis can be used to more accurately use coupon testing for assessment of impact damage. The approach to analysis can be separated into two parts; (1) predicting the structural response of a composite to impact loading, which defines the extent of impact damage; and (2) predicting the structural response of the damaged composite to service loading. The latter, in theory, ought to be able to define the appropriate scaling laws for coupon test and full scale test. Both approaches rest on the availability of either (1) accurate micromechanical models to predict progressive failure phenomena or (2) empirical correlation of damage with degradation of composite structural properties.⁸² The review of analytical methods is divided into identifying specific computational modeling that is available for micromechanical treatments, and review of empirical approaches.

Empirical Methods

The empirical approach is typically used since the development of accurate micromechanical models depends on knowledge of the local failure mechanisms, their influence on macroscopic failure (constitutive relationships), and effective computational models that require finite element modeling (FEA). The latter two topics are the subject of current research and the entire field is dynamically changing. Because of this, past efforts to develop damage tolerance/fracture control

for FWC cases has relied on an empirical approach that is typified by the work of Beckwith.⁸³ Micromechanical methods are seldom used at this scale, although macroscopic fracture mechanics may be used in finite element modeling (FEM) of the testing. The absence of micromechanical models means the actual local damage must be treated at a higher geometric scale and use empirical constitutive relationships that may not be based on accurate micromechanical phenomena. In such cases, one is never sure if the empirical relationships are being extrapolated beyond their limits of validity. Furthermore, a truly valuable micromechanical model based on valid failure mechanisms will utilize progressive failure analysis. This requires very accurate constitutive models at the pre-failure, failure and post-failure level.⁸³

These difficulties with empirical approaches^{5,73} are one reason unpredictable effects of scale are observed. In such cases, it is not possible to safely predict full scale structural response based on geometric scaled tests. The empirical approach requires an after the fact correlation of coupon and full scale test data to define safety criteria. Compounding both approaches is the fact that predictions and results are specific to individual resins, fibers and manufacturing practices. The experience cited by Verderaine in these two references show the difficulties faced by an empirical approach when starting without the luxury of accurate analytical models.

Analytical Methods

A number of analytical models based on finite element methods have been developed for analyzing the micromechanical response of composite structures. Most effort has been applied to modeling plate response although the treatments of shells and cylinders is growing. For example, Tolbert^{84,85} has used traditional composite-lamination theory to describe the stiffness response of FWC cylinders. He uses macromechanical models of composite cylinders to model the constitutive relationships for cylinder walls. Properties of fibers (E_1 , E_2 , G_{12} , and ν_{12}) and matrix were varied and rule of mixture models used for the composite properties. This model was not extended to predict the local reduction in composite stiffness or strength due to damage. The basic limitation of classical lamination theory is that it treats the shell as a homogeneous material by the use of constitutive relationships that scale the intrinsic microscopic phenomena. It cannot accurately treat progressive failure phenomena at the sublaminar region. It can be used, however, in a quasi-three dimensional way by applying the model at the lamina level rather than the shell level⁸⁶.

CODSTRAN

Another group of workers⁸⁷⁻⁹⁵ have developed an analytical model for treatment of composite durability called CODSTRAN(Composite Durability Structural Analysis) and CISTRAN(Composite Impact Structural Analysis). This model treats damage and fracture in composite thin shells. CODSTRAN was developed to perform buckling analysis. The code is readily applied to stiffened composite shells, and cylinders and has the ability to model damage initiation, growth and accumulation up to the stage of propagation to fracture. It accommodates combined structural loading conditions. The authors discuss the failure criteria used in the code by Chamis.⁹⁰ The code utilized micromechanical treatments based on the physics of composite

mechanics at a local level. Finite element methods are used to quantify the structural behavior. While designed primarily for buckling analysis the model accommodates progressive fracture and can be used as a deformation simulation tool. Recently the authors applied the code to model the effects of fiber fracture on the load carrying capability of a composite cylindrical shell under internal pressurization.⁸⁷ The importance of local damage on structural durability of such pressurized shells is noted.

DACSIL

The earlier work of Yener, et al.⁸² pursued a somewhat similar approach of developing a progressive failure analysis for determining the effects of impact damage in composite cylinders. These authors developed a code called DACSIL (Damage Assessment of Composite Structures subjected to Impact Loading) that uses progressive failure analysis and defines constitutive relationships for the three regimes of material response, pre-failure (linear elastic behavior), failure (fiber failure), and post-failure (no load carrying ability after fiber failure). These criteria are consistent with the observations of Poe.^{6,18-20} The code uses the direct integration by the explicit integration method in the FEA. Solid degenerated elements are modified to accommodate transverse shear phenomena. This code is described in this citation and several additional citations in its bibliography. Yener points out the significant limitation of the work is the absence of enough experimental data at coupon and full scale level to validate the assumptions on failure criteria, materials analyses to develop and support microscopic constitutive relationship, and problems with solution procedures for the FEA.

DYNA3D

DYNA3D is the latest in a series of computer codes designed to treat dynamic structural deformation response of materials under external loading. It is based on physical models of hydrodynamics and has extensions capable of treating a variety of phenomena from fracture of metals under high strain rate deformation (ballistics) to impact damage of composites. Lindberg⁹⁶ discusses the application of DYNA3D to fiber reinforced composite damage models and compares predictions of models to available experimental data. He evaluated fiber failure under biaxial tensile and compressive stresses, and matrix failure under combined transverse fiber tensile and compressive stress, and shear stress.

STAGS

One of the earlier modeling programs for treating the problem of compressive buckling was developed by Almroth.⁹⁷⁻¹⁰⁰ STAGS is intended for the analysis of shell structures. The code does not appear to be based on micromechanical models although it may for the basis to incorporate micromechanical models that can develop constitutive relationships the code can utilize. Almroth has presented a summary of relevant literature, primarily related to buckling phenomena.¹⁰¹

FANDEP

If sufficiently accurate FEA techniques and constitutive relationships are available, in order to provide analytical tools for the predictive behavior of structural response to damage one must be able to utilize the geometric characterization of damage by NDE methods. Frankle¹⁰² describes a computational "preprocessor" that takes ultrasonic test(UT) and X-ray computed tomography(CT) output and produced an input file for the geometric description of data into the finite element mesh used for micro/macromechanical treatments. This preprocessor is called FANDEP(FAntastic® NDE Preprocessor).

This approach uses additional computer codes developed to correlate NDE parameters with material properties. The specific code, called NDECOR, was developed by Boeing.¹⁰³ The use of NDECOR follows the approach defined in the Air Force IUS Scan Criteria project.¹⁰⁴ This particular code may not be essential as other investigators have similar objectives: to produce a definition of local mechanical properties in a damaged region by suitable reduction of the NDE signals(see for example, citations 32,37,40,105). The FANDEP program was demonstrated to effectively use user supplied UT and CT(GE 9800 scanner) files to create an finite element model of specific defects in composite parts with mechanical properties derived from the NDE parameters by NDECOR. Limited data was available to fully characterize the matrix of elastic stiffness, only cross-ply elastic modulus, cross-ply/warp shear modulus, ultimate tensile strength in cross-ply and ultimate shear strength in cross-ply/warp directions was used. A comparison of FANDEP geometric distribution of defects agreed with the baseline NDE data, However, the specific sample specimen did not allow validation of the consistency of predicted and observed mechanical properties due to the limited set of properties predicted by FANDEP. Computations and preprocessing of NDE data were conducted on a SUN 3/180 work station requiring on the order of 2 hours processing time.

On the basis of the experimental observations of Poe it would appear that an analytical method of progressive failure using FEA would be possible for the situation for pressurized rocket motor cases whose critical failure mechanism is hoop tensile failure.^{6,18-20} Low velocity impact damage of filament wound cylinders creates local damage in the form of cracked fibers and matrix cracks. Small matrix cracks confined within a ply layer can be considered incipient delaminations. The pre-failure criteria described by Yener⁸² as being defined by the fiber tensile behavior is appropriate based on the work of Poe. The failure criteria, broken fibers(ligament), and post-failure criteria, no load carrying by the broken ligament, also seems appropriate on the basis of the work of Poe, et al. Poe observed that the failure of the ligament results in no further load carrying capability of the ligament.

Summary

The analysis of failure of an impact damaged, thick rocket motor case will require an accurate progressive failure model. This model will be underpinned by a characterization of the micromechanical behavior of the thick cases. Since the case is thick and the effect of loading under low velocity impact is complex, a 3-D analysis code, or a quasi-3 dimensional code, will

almost certainly be necessary for accurate understanding of the behavior of microstructure. NDECOR may be a good starting point for use of NDE data. The model of the CODSTRAN code extended to tensile failures, or DACSIL, may be useful. While Dyna3D may be a useful analysis tool, it is worthwhile to evaluate the newer analysis programs under development in the university and Federal Laboratory environments.

X. SUMMARY AND RECOMMENDATIONS

- Impact Damage phenomena

Although there are discrepancies between the work of Poe and others in defining impact damage, a reasonably consistent picture emerges. Low velocity impact damage is strongly influenced by the thickness of the composite and the width of support span. Thin composites and large support spans allow flexure of the composite with attendant tensile loading on the backside. This can contribute to delamination and backface damage. Thicker composites and composites backed with appreciable stiff material show less flexure and damage is concentrated on the near front surface volume due to the compressive and shear loading of the matrix. The effect of progressive ply delamination observed by Poe in tensile testing subscale thick cases appears clearly related to the fabrication process, but is intriguing. Such failures frequently resulted in a higher strength unfailed ligament. Delamination may result in a strengthening of the composite since the delamination reduces the stress concentration on the impact damage. Similar effects might be observed by changing the hoop angle orientation within the constraints imposed by the case geometry.

- Effective NDE Methods to quantify damage

Quantification of damage serves two purposes. In service it identifies and characterizes the extent of damage in the composite. NDE quantification also supports the development and use of micromechanical deformation models that can be used to predict residual strength and failure mechanisms of in-service cases that have been damaged.

NDE methods can be grouped into contact and non-contact methods. The latter are of most interest for the current rocket motor case. The more promising methods are vibrothermography, for example, SPATE, that can serve as a large area, rapid inspection tool. This tool will allow examination of the large case to identify suspected damaged areas. Pulse-echo acousto-ultrasonic methods such as Thermo-Acoustic Photonic NDE, and conventional pulse-echo C-scan methods used with real time signal processing will allow single side characterization of suspected damage sites at a higher resolution than vibrothermography. These tools could be developed for service prediction of residual strength given the available micromechanical models to correlate with observed geometric damage. Backscatter X-ray computed tomography, a developmental tool offers the promise of the best spatial resolution. Conventional CT methods have the best spatial resolution and will be very useful in developing

the geometric characterization of damage necessary for accurate micromechanical models of mechanical behavior.

- Critical coupon level tests

The critical design criterion for rocket motor cases is the biaxial tensile strength (hoop-axial). this is a difficult condition to simulate. Previous testing by Poe pointed out both the difficulty of uniaxial testing the hoop strength of large thickness samples with conventional gripping systems, and of obtaining realistic microstructural samples of the candidate materials. The use of a hoop tensile test in which a relatively tall cylinder is tested by the frictionless expansion of an inner support ring may more accurately indicate the effects of damage on hoop tensile strength. One possible approach could repeat some of Poe's thick cylinder work using regularly wound cylinders and such a test method. An improvement of the biaxial cylinder testing of Swanson that used an internally pressurized cylinder might be a fruitful approach although the experimental difficulties appear significant with this test method.⁵

Although effective geometric scaling is a significant issue in the present instance, a larger problem of achieving scaled test results may be the significant time difference in fabrication and the effects on resin properties.

- Relationship of Manufacturing Process Variables with Impact Damage Tolerance

As mentioned in the previous section, the comparison of subscale cylinders with full scale cylinders should use comparable manufacturing processing. This means the subscale cylinders should be manufactured using the resin out times and fiber handling used in full scale cylinders. Microstructural variables play an important role in improving impact damage. Particular variables of importance is the fiber-matrix interface. This can be modified by pre-treatment of the fiber and the use of matrix modifiers as discussed by Cantwell and Morton. A significant options to improve impact tolerance may be to fully understand the effects of the long out times used in full scale filament winding and improve them.

- Analytical Modeling of Damage for a Damage Tolerant Philosophy

Developing a strong analytical method for predicting the results of impact damage may have the greater benefit. The use of accurate NDE characterization to define geometric and elastic properties for input into 3-D analysis codes should for the basis of this modeling. The development of a progressive failure model in the analysis should allow detailed understanding of failure and the effects of microstructural parameters which could subsequently be optimized. Such analysis tools will serve two purposes, given accurate geometric characterization of damage of full scale articles and accurate elastic characterization by acoustic polling, accurate residual strengths could be predicted. Secondly, these tools allow understanding of important microstructural characteristics that can be improved by materials and process development.

In summary, an effective approach to impact damage analysis and control would incorporate a micromechanical analysis development program that used CT and other NDE methods to provide accurate characterization of geometric damage in test coupons. This approach would refine and validate the micromechanical analysis by producing subscale cylinders and testing them in test methods that closely represent the true stress state expected in service. The micromechanical models should be based on either exiting codes or new ones if evaluation proves it is needed.

These analysis tools would be used to support a full scale inspection method that used tools such as vibrothermography for wide area scans of rocket motor cases to identify possible damage sites, and tools such as single sided pulse-echo methods with synthetic apertures and advanced signal processing to characterize local damage accurately. Pulse-echo methods could include acoustic methods and eventually back scattered x-ray computed tomography.

The ability to scale test results will depend on using test methods that reproduce the desired stress state in subscale coupons and the availability of accurate micromechanical models that predict the evolution of damage under the appropriate applied stress state.

XI. BIBLIOGRAPHY

1. M. J. Robinson, R.O. Charette, B. G. Leonard, "Advanced Composite Structures for Launch Vehicles," SAMPE Quarterly, Vol. 22, No. 1, Jan. 1991, pages 26-37.
2. K. B. Sanger, H. D. Dill, E. F. Kautz, "Certification Testing Methodology for fighter Hybrid Structure," Composite Materials: Testing and Design(Ninth Volume), ASTM STP 1059, edited by S. P. Garbo, American Society for Testing and Materials, Philadelphia, 190, Pages 34-47.
3. Suresndra N. Singhal, Christos Chamis, "Design for Inadvertent Damage In Composite Laminates," International SAMPE Electronics Conference Proceedings, Vol. 24, (1992), pages 256-269.
4. R. Jones, J. Paul, J. F. Williams, "Assessment of the Effect of Impact Damage In Composites," Composite Structures, vol. 10, No. 1(1988), p51-73.
5. V. Verderaiame, M. Rheinfurth, "Identification and Management of Filament-Wound Case Stiffness Parameters," NASA Technical Paper 2117, published by National Aeronautics and Space Administration, Huntsville, AL. George C. Marshall Space Flight Center, Jan. 1983, 17 p.
6. C. C. Poe, "Summary of a Study to Determine Low-Velocity Impact Damage and Residual Tension Strength for a Thick Graphite/Epoxy Motor Case," NASA Technical Memorandum 102678, published by National Aeronautics and Space Administration, Hampton, VA. Langley Research Center, 36p, June 90
7. P. R. Evans, "Composite Motor Case Design," in Design Methods in Solid Rocket Motors, AGARD Lecture Series No. 150, 1988 Revision, published by Advisory Group for Aerospace Research and Development, 7 Rue Ancelle 92200 Neuilly-sur-Seine (France), 242p, pages 1-1 to 1-4.
8. J. P. Denost, "Design of Filament-wound Rocket Cases," in Design Methods in Solid Rocket Motors, AGARD Lecture Series No. 150, 1988 Revision, published by Advisory Group for Aerospace Research and Development, 7 Rue Ancelle 92200 Neuilly-sur-Seine (France), 242p, pages 5-1 to 5-22(1988).
9. Morton Thiokol, Inc., Brigham City, UT. Space Div., "Block 2 SRM (Solid Rocket Motor) Conceptual Design Studies. Volume 1, Book 1: Appendix A: CEI (Contract End Item) Specification CPW1-1900, Appendix B: Composite Motor Case," Final Report, NASA Report Number NAS 1.26:179049, MTI-PUB-87354-V-1-BK-1-APP, 171p, NASA Contract Number NAS8-37296, National Aeronautics and Space Administration, Washington, DC., December 19, 1986.

10. Hercules, Inc., Cumberland, Md. Allegany Ballistics Lab, "Filament Wound Rocket Motor Chambers," Final Report, NASA Contract NAS7-100, JPL-954136, NASA Report NASA-CR-149861, 68p, September, 1976
11. Stephen R. Swanson, J. D Spacecraft Rockets, "Strength Design Criteria for Carbon/Epoxy Pressure Vessels," vol. 27, No. 5(Sept.-Oct. 1990), pages 522-526.
12. V. F. Neraka, Yale Chang, J. E. Grady, D. A. Trowbridge, "Application of Composite Materials To Impact-Insensitive Munitions," Johns Hopkins APL Technical Digest, Vol. 13, No. 3(1992)pages 418-424.
13. M. Yener, E. Wilcott, "Damage Assessment Analysis of Composite Pressure Vessels Subjected to Random Impact Loading," J. Pressure Vessel Technology, Transactions of ASME, vol. 111(May 1989), pages 124-129.
14. G. K. Knight, "Residual Strength of Carbon/Epoxy Pressure Vessels Subjected to low Velocity Impacts," Proceedings of ANTEC 89 - 47th Annual Technical Conference of SPE, Society of Plastics Engineers, Brookfield Center, CT(1989), pages 1486-1490.
15. W. J. Cantwell and J. Morton, "The Impact Resistance of Composite Materials - A Review," Composites, vol. 22, No. 5,(1991) pages 347-362.
16. W. J. Cantwell and J. Morton, "An Assessment of the Residual Strength of an Impact-Damaged Carbon Fibre Reinforced Epoxy," Composite Structures, vol. 14(1990) pages 303-317.
17. E. Demuts, "Low Velocity Impact in a Graphite/Epoxy," in Collection of Papers - AIAA/ASME Structures, Structural Dynamics and Materials Conference, pt 2, 1993, published by AIAA, Washington, DC, USA, p901-908
18. C. C. Poe, W. Illg, and D. P. Garber, "Tension Strength of a Thick Graphite/Epoxy Laminate after Impact by a 1/2-in. Radius Impactor," NASA Report ,NAS 1.15:87771, 130p, National Aeronautics and Space Administration, Hampton, VA. Langley Research Center, July 1986
19. C. C. Poe, W. Illg, "Strength of a Thick Graphite/Epoxy Rocket Motor Case After Impact by a Blunt Object," NASA Technical Memorandum 89099, published by National Aeronautics and Space Administration, Hampton, VA. Langley Research Center, 53p, February 1987
20. C. C. Poe, "Simulated Impact Damage In A Thick Graphite/Epoxy Laminate Using Spherical Indenters," NASA Technical Memorandum 100539, published by National Aeronautics and Space Administration, Hampton, VA. Langley Research Center, 35p, January 1988.

21. C. F. Buynak, T. J. Moran, S. Donaldson, "Characterization of Impact Damage in Composites," SAMPE Journal, v 24, n 2(Mar-Apr. 1988) p 35-39.
22. A. Palazotto, G. E. Maddux, B. Horban, "The Use of Stereo X-Ray and Depty Techniques for Evaluating Instability of Composite Cylindrical Panels with Delaminations," Experimental Mechanics, June 1989, p144-151.
23. B. Wilder, A. Palazotto, "Study of damage in curved composite panels," Proceedings of Conference on Engineering, Construction, and Operations in Space: Proceedings of Space 88, Albuquerque, NM, USA, August 29-31,1988, published by ASCE, New York, NY(1988), p 518-528.
24. A. Palazotto, R. Perry, R. Sandhu, "Impact response of graphite/epoxy cylindrical panels," AIAA Journal, v 30, n 7(July 1992), p 1827-1832.
25. Y. L. Bai, J. Harding, "Fracture Initiation In Glass Reinforced Plastics Under Impact Loading", Proceedings of the 3rd Conference on Mechanical Properties at High Rates of Strain, Oxford, 1984, Institute of Physics Conference Series n 70, published by Institute of Physics, Bristol and London, England, p 339-340
26. M. P. Clarke, M. J. Pavier, "Artificial Damage Techniques for Low Velocity Impact in Carbon Fiber Composites," Proceedings of the 7th International Conference on Composite Structures, August, 1993, Paisley, Scotland, published in Composite Structures, v 25, n 1-4(1993), p 113-120
27. W. J. Cantwell and J. Morton, "The Significance of Damage and Defects and Their Detection In composite Materials: A Review," Journal of Strain Analysis, Vol. 27, No. 1(1992) pages 29-42.
28. John E. Masters, ed. Proceedings of the International Symposium on Damage Detection and Quality Assurance in Composite Materials," San Antonio, TX, November 13-14, 1990, International Symposium on Damage Detection and Quality Assurance In Composite Materials, ASTM Special Technical Publication 1128(1992), published by American Society for Testing and Materials, Philadelphia, PA,
29. Travis N. Blalock, "Detection of Fiber Damage In A Graphite Epoxy Composite Using Current Injection and Magnetic Field Mapping," in Proceedings of the Twelfth Annual Review of Progress In Quantitative Nondestructive Evaluation, Williamsburg, VA, Review of Progress In Quantitative Nondestructive Evaluation, Vol. 5B, Plenum Press, New York, pages 1207-1213.
30. Harold E. Kautz, "New Acousto-Ultrasonic Techniques Applied to Aerospace Materials," NASA Technical Memorandum, No. 101299,(1988), 20 p.

31. T. M. Cordell , P. K. Bhagat, "Air Force requirements for NDE of Composite Materials," proceeding of the Winter Annual Meeting of the American Society of Mechanical Engineers Atlanta, GA, USA December 1-6, 1991, in Enhancing Analysis Techniques for Composite Materials American Society of Mechanical Engineers (Publication) NDE, vol. 10, Published by ASME, New York, NY, USA.(1991), pages 67-75.
32. Alex Vary, "The Acousto-Ultrasonic Approach," NASA Technical Memorandum 89843, Lewis Research Center, (1987), 30p.
33. H. E. Kautz, "Ultrasonic Evaluation of Mechanical Properties of Thick, Multilayered, Filament-Wound Composites," Materials Evaluation, vol. 45, December 1987, pages 1404-1412.
34. H. E. Kautz., "Acousto-Ultrasonic Verification of the Strength of Filament Wound Composite Material," NASA Report NAS 1.15:88827, E-3201, 24 pages, Lewis Research Center, Cleveland, OH,(1986); also Presented at the Pressure Vessel Conference, Chicago, IL., 21-24 Jul. 1986; Sponsored by the American Society of Mechanical Engineers
35. National Aeronautics and Space Administration, Washington, DC, "Measuring the Interlaminar Shear Strengths of Composites: An Ultrasonic Technique Performs Nondestructive Tests," NTIS Technical Note, report order number N86-10561. March 1988
36. Lisa A. Tardiff and Bradley M. Taber III, "Ultrasonic Inspection of Filament Wound Graphite Epoxy Cylinders," U. S. Army Materials Technology Laboratory Report MTL-TR-092-61, Watertown, MA, (1992), 30 pages.
37. M. A. Awal, T. Kundu, "Material characterization of Composites by Acoustic Microscopy," proceeding of the Winter Annual Meeting of the American Society of Mechanical Engineers Atlanta, GA, USA December 1-6, 1991, in Enhancing Analysis Techniques for Composite Materials American Society of Mechanical Engineers (Publication) NDE, vol. 10, Published by ASME, New York, NY, USA.(1991), pages 1-7
38. K. V. Steiner, "Defect Classifications in Composites Using Ultrasonic Nondestructive Evaluation Techniques," Proceedings of the International Symposium on Damage Detection and Quality Assurance in Composite Materials," San Antonio, TX, November 13-14, 1990, International Symposium on Damage Detection and Quality Assurance In Composite Materials, ASTM Special Technical Publication 1128, John E. Masters, ed., published by American Society for Testing and Materials, Philadelphia, PA, USA,(1992) pages 72-84
39. L. Leonard, "Testing for Damage," Advanced Composites, vol. 6(1991), pages 40-45.
40. M. Ourak, B. Nongaillard, J. M. Rouvaen, M. Ouaftouh, "Ultrasonic Spectroscopy of Composite Materials," NDT International, vol. 24, no. 1(February 1991) pages 21-28.

41. P. H. Johnston, D. Kishoni, "Practical Application of State-of-the-Art NDE Techniques: Evaluation of Graphite-Epoxy Composite Wing covers," Review of Progress in Quantitative Nondestructive Evaluation, vol. 7B, 1988, pub. by Plenum Press, NY, USA, pages 995-1001.
42. R. B. Thompson, D. O. Thompson, D. K. Holger, D. K. Hsu, M. S. Hughes, E. P. Papadakis, Y. -M. Tsai, L. W. Zackery, "Ultrasonic NDE of Thick Composites," proceeding of the Winter Annual Meeting of the American Society of Mechanical Engineers Atlanta, GA, USA December 1-6, 1991, in Enhancing Analysis Techniques for Composite Materials American Society of Mechanical Engineers (Publication) NDE, vol. 10, Published by ASME, New York, NY, USA.(1991), pages 43-57.
43. R. J. Andrews, R. W. Martin, " Backscatter B-Scan Images of Defects in Composites," Review of Progress in Quantitative Nondestructive Evaluation v 5B, published by Plenum Press, New York, NY, USA, pages 1189-1198.
44. C. P. Burger, "Non Contacting Testing and NDT for Composite Shells," proceedings of the 1988 ASME Pressure Vessels and Piping Conference, Pittsburgh, PA, June 19-23, 1988, David Hui and T. J. Kozik, eds., PD-vol. 18, published by The American Society of Mechanical Engineers, NY, NY(1988), pages 167-171.
45. N. A. Schumacher, C. Duffer, C. P. Burger, "Non-Contact Non-Destructive Evaluation of Composite Panel With Plate Waves," Proceedings of the 14th Annual Energy-Sources Technology Conference and Exhibition, Houston, TX, USA, January 20-23, 1991: Composite Material Technology - 1991, American Society of Mechanical Engineers, Petroleum Division (Publication) PD v 37, published by ASME, New York, NY, USA. pages 219-223.
46. T. J. Lewis, "STA-2A NDT Testing," Final Report NASA Contract Report NAS 1.26:179301, TWR-17748, 117p, NASA Contract NAS8-30490, National Aeronautics and Space Administration, Washington, DC., November 25, 1987
47. L. B. Greszczuk, R. J. Miller, "Advanced Design Concepts for Buckling-Critical Composite Shell Structures," Journal of Aircraft, vol. 8, no. 5(1971), pages 363-373.
48. W. T. Yost, John H. Cantrell, "Surface Generation and Detection of Coupled Fiber-Matrix Mode Acoustic Wave Propagation In Fiber-Reinforced Composites," Review of Progress in Quantitative Nondestructive Evaluation v 5B, published by Plenum Press, New York, NY, USA, pages 743-760.
49. L. H. Tenek, E. G. Henneke, II, "Flaw Dynamics and Vibrothermographic-Thermoelastic NDE of Advanced Composite Materials, Proceeding of Thermosense XVII, Orlando, FLA., April 3-5, 1991, vol. 1467, pub by The International Society for Optical Engineering, Bellingham, WA, USA(1991), pages 252-263.

50. Tenek, Lazarus H., Henneke, Edmund G. II, Gunzburger, Max D., "Vibration of Delaminated Composite Plates and Some Applications to Non-destructive Testing," *Composite Structures*, vol. 23, n 3, p 253-262, (1993).

51. C. Caneva, S. Olivieri, C. Santulli, G. Bonifazi, "Impact Damage Evaluation on Advanced Stitched Composites by Means of Acoustic Emission and Image Analysis," *Proceedings of the 7th International Conference on Composite Structures*, August, 1993, Paisley, Scotland, published in *Composite Structures*, v 25, n 1-4 (1993), p 121-128.

52. W. P. Chu., "Investigation of Laser Holographic Interferometric Techniques for Structure Inspection," *NASA Final Technical Report NASA-CR.-132344*, Old Dominion Univ. Research Foundation, Contract Number NGR-47-003-069, Oct 1973, 47p

53. Claude Bathias, Andre Cagnasso, "Application of X-Ray Tomography to the Nondestructive Testing of High-Performance Polymer Composites," *Proceedings of the International Symposium on Damage Detection and Quality Assurance in Composite Materials*, San Antonio, TX, November 13-14, 1990, International Symposium on Damage Detection and Quality Assurance In Composite Materials, ASTM Special Technical Publication 1128, John E. Masters, ed., published by American Society for Testing and Materials, Philadelphia, PA, USA, (1992)

54. Robert N. Yancey, Jerel A. Smith, "Non-destructive Evaluation of Advanced Composites Using High-Resolution Computed Tomography" 22nd International SAMPE Technical Conference, Boston, MA, USA, November 6-8, 1990, Advanced Materials: Looking Ahead to the 21st Century, National SAMPE Technical Conference, vol. 22, Published by SAMPE, Covina, CA, USA, pages 998-1007

55. J. H. Kinney, T. M. Breunig, T. L. Starr, D. Haupt, M. C. Nichols, S. R. Stock, M. D. Butts, R. A. Saroyan, "X-Ray Tomographic Study of Chemical Vapor Infiltration Processing of Ceramic Composites," *Science*, vol. 260 (1993) pages 789-791.

56. S. W. Beckwith, M. E. Morgan, J. R. Kapp, G. P. Anderson, "Damage Tolerance/Fracture Control Approach TO Graphite /Epoxy Filament Wound Case (FWC) For Space Shuttle Motors," *International SAMPE Symposium and Exhibition*, vol. 32, SAMPE, Covina, CA (1987), pages 1528-1543.

57. V. L. Chen (McDonnell Douglas Aerospace, Transport Aircraft, Long Beach, CA, USA), H. T. Wu (McDonnell Douglas Aerospace, Transport Aircraft, Long Beach, CA, USA), K. T. Kedward (University of California, Santa Barbara), "Assessing the Impact Resistance of Contemporary Composite Structures, in progress,

58. Stephen R. Swanson, "Scaling of Impact Damage in Fiber Composites From Laboratory Specimens to Structures," *Proceedings of the 7th International Conference on Composite Structures*, August, 1993, Paisley, Scotland, published in *Composite Structures*, v 25, n 1-4 (1993), pages 249-255.

59. Victor L. Chen, Hsi-Yung Wu, Hsi-Yang Yeh, "Parametric Study of Residual Strength and Stiffness for Impact Damaged Composites," Proceedings of the 7th International Conference on Composite Structures, August, 1993, Paisley, Scotland, published in Composite Structures, vol. 25, n 1-4(1993) , pages 267-275

60. S. R. Swanson, Y. Qian, "Experimental Measurement of Impact Response in Carbon/Epoxy Plates," AIAA Journal, vol. 28(1990), pages 1069-1074.

61. S. R. Swanson, N. L. Smith, Y. Qian, "Analytical and Experimental Strain Response in Impact of Composite Cylinders," Composite Structures, vol. 18(1991), pages 95-108.

62. A. P. Christoforou, S. R. Swanson, "Analysis of Simply-Supported Orthotropic Cylindrical Shells Subject to Lateral Impact Loads," Journal of Applied Mechanics, vol. 57(1990), pages 376-382.

63. Swanson, Stephen R., "Scaling of impact damage in fiber composites from laboratory specimens to structures," Composite Structures, vol. 25, n 1-4, p 249-255(1993). 53. K. T. Kedward, Private communication(1993), University of California, Santa Barbara.

64. P. Robinson, G. A. O. Davies, "Impactor Mass and Specimen Geometry Effects In Low Velocity Impact of Laminated Composites," International Journal of Impact Engineering , vol. 12, No. 12,(1992) pages 189-207.

65. K. T. Kedward, Private communication(1993), University of California, Santa Barbara.

66. Sjoblom, Peter, "Simple Design Approach Against Low-Velocity Impact Damage," International SAMPE Symposium and Exhibition vol. 32. Published by SAMPE, Covina, CA, USA p 529-539(1987) proceeding of 32nd International SAMPE Symposium and Exhibition: Advanced Materials Technology '87. Anaheim, CA, USA, April 06-09, 1987.

67. Heller, M., Ryall, T. G., Jones, R, "Thermomechanical Assessment of Damage in Composites," Theoretical Applied Fracture Mechanics, vol. 13, n 2, p 145-153(May 1990).

68. Kellas, Sortiris, Morton, John, "Strength Scaling in Fiber Composites," AIAA Journal, vol. 30, n 4, p 1074-1080(Apr. 1992).

69. Kellas, S, Morton, J, "Strength Scaling in Fiber Composites," Final Report, NASA Report Number NAS 1.26:4335, 60p, NASA Contract Number NAS1-18471, National Aeronautics and Space Administration, Washington, DC.(June 1992).

70. Obrien, T. K. and Salpekar, S. A., "Scale Effects on the Transverse Tensile Strength of Graphite Epoxy Composites," NASA Report Number NAS 1.15:107637, AVSCOM Report Number AVSCOM-TR-92-B-009, 60p, Contract Number RTOP 505-63-50-04, National Aeronautics and Space Administration, Langley Research Center, Hampton, VA.(June 1992) also

presented at the 11TH ASTM Symposium on Composite Materials: Testing and Design, Pittsburgh, PA, 4-5 May 1992

71. T. L. Anderson, and S. Yongqi, " Mechanics of Fractal Damage," Final Report, AFOSR Report Number CMC-6730-15, Grant Number AFOSR-90-0373, 35p, Air Force Office of Scientific Research, Bolling AFB, DC.,(March 30, 1992).

72. T. J. Lu, X. Ji, X. R. Gu, "Effect of Resin Properties On The Strength of Filamentary Structures," Journal of Strain Analysis for Engineering Design, Vol. 24, No. 2(April 1989), pages 107-113.

73. V. Verderaime, "Development of In Situ Stiffness Properties for Shuttle Booster Filament Wound Case," NASA Technical Paper 2377, George Marshall Flight Center, August 1984, 57p.

74. E. M. Pearce, J. Mijovic, "Characterization-Curing-Property Studies of HBRF 55A Resin Formulations," Final Report, NASA Report NAS 1.26:175836, 133p, NASA Contract Number NAG2-229, National Aeronautics and Space Administration, Washington, DC., January 31, 1985.

75. F. E. Stone, "Study of Residual Stresses in Thick Glass Filament Reinforced Laminates," Quarterly Progress Report. No. 3, 30 Dec. 64-30 Mar 65, .Report Number SM-47833, 2p, Contract Number NO90301, Project Number R007 03 04(March 1965).

76. Ray L. Dempsey, Ray E. Horton, "Damage Tolerance Evaluation of Several Elevated Temperature Graphite Composite Materials," Proceedings of 35th International SAMPE Symposium and Exhibition -Advanced Materials: the Challenge for the Next Decade, Anaheim, CA, USA, April 4-5, 1990, National SAMPE Symposium and Exhibition (Proceedings) v 35, in Book 2. pub. by SAMPE, Covina, CA, USA,. pages 1292-1305

77. Teh, Kuen Tat, Morton, John, "Impact Damage Development and Residual Compression performance of Advanced Composite Material Systems," Collection of Technical Papers - AIAA/ASME Structures, Structural Dynamics and Materials Conference pt 2, p 877-886, Published by AIAA, Washington, DC, USA. (1993)

78. W. D. Bascom, and L. T. Drzal, " Surface Properties of Carbon Fibers and Their Adhesion to Organic Polymers," NASA Report NAS 1.26:4084, 96p, NASA Contract NAS1-17918, Hercules, Inc., Magna, UT. Bacchus Plant Lab. National Aeronautics and Space Administration, Washington, DC., July 1987.

79. W. D. Bascom, "Interfacial Adhesion of Carbon Fibers. Final Report, November 1984-October 1986", NASA Report NAS 1.26:178306, 53p, NASA Contract Number NAS1-17918, Hercules, Inc., Magna, UT. Aerospace Div., National Aeronautics and Space Administration, Washington, DC., August 1987

80. J. T. Paul, Jr., and G. A. Buntin, "Graphite Fiber Surface Treatment to Improve Impact Strength and Fracture Resistance in Subsequent Composites," Final Report, NASA Report Number NAS 1.26:165901, 43p, NASA Contract Number NAS1-15869, Hercules, Inc., Wilmington, DE., National Aeronautics and Space Administration, Washington, DC., December 1982.

81. Dauksys, R. J., "Coupling of Epoxy Polymers to Graphite Fibers," AFML-TR-72-23, 64p, Air Force Materials Lab Wright-Patterson AFB Ohio, (May 1972).

82. M. Yener, M. ASCE, E. Wolcott, "Progressive Impact Damage Assessment in Composite Pressure Vessels," Proceedings of Conference on Engineering, Construction, and Operations in Space: Proceedings of Space 88, Albuquerque, NM, USA, August 29-31, 1988, published by ASCE, New York, NY(1988), p 552-563.

83. S. W. Beckwith, M. E. Morgan, J. R. Knapp, P. G. Anderson, "Damage Tolerance/Fracture Control Approach to Graphite/Epoxy Filament Wound Case (FWC) for Space Shuttle Motors," Proceedings of 32th International SAMPE Symposium and Exhibition, Anaheim, CA USA, April 6-9, 1987,-National SAMPE Symposium and Exhibition (Proceedings) v 32, pub. by SAMPE, Covina, CA, USA(1987), pages 1528-1543.

84. "Stiffness Properties of Laminated Graphite/Epoxy Cylinders, NASA Technical Brief, 88-0482, June 1988, published by NASA Technology Transfer Division, BWI Airport, MD, USA

85. R. Noel Tolbert, "Stiffness Properties for Dynamic Modeling of Composite Graphite-Epoxy Cylindrical Shells," NASA Contract Report MFS-27157, NASA Marshall Space Flight Center, Huntsville, AL

86. T. Nishiwaki, A. Yokoyama, Z. I. Maekawa, H. Hamada, Y. Maekawa, S. Mori, "A Simplified Tensile Damage Method for Composite Laminates Using a Quasi-Three Dimensional Model," Proceedings of the 7th International Conference on Composite Structures, August, 1993, Paisley, Scotland, published in Composite Structures, v 25, n 1-4(1993), p 61-67

87. L. Minnetyan, C. C. Chamis, P. L. N. Murthy, "Damage and Fracture in Composite Thin Shells," NASA Technical Memorandum 105289, National Aeronautics and Space Administration, Cleveland, OH. Lewis Research Center (1991), 26 p..

88. C. C. Chamis, C. A. Ginty, "Fiber Composite Structural durability and Damage Tolerance: Simplified Predictive Methods," NASA Technical Memorandum 100179, National Aeronautics and Space Administration, Cleveland, OH. Lewis Research Center (1987).

89. C. C. Chamis, G. T. Smith, "CODSTRAN: Composite Durability Structural Analysis," NASA Technical Memorandum 79070, National Aeronautics and Space Administration, Cleveland, OH. Lewis Research Center,(1978).

90. C. C. Chamis, and P. L. N. Murthy, "Computational Simulation of Structural Fracture in Fiber Composites," in NASA Langley Research Center, Eighth DOD/NASA/FAA Conference on Fibrous Composites in Structural Design, Part 1 p 355-371, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH.(September 1990).

91. C. C. Chamis, "Integrated Analysis of Engine," NASA Report Number NASA-TM-82713, E-995, 24p, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH., 1981.

92. L. Minnetyan, J. M. Rivers, P. L. N. Murthy, and C. C. Chamis, "Structural Durability of Stiffened Composite Shells," NASA Report Number NAS 1.26:190588, 33p, NASA Contract Number NAG3-1101, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH.(1992), also presented at the 33RD Structures, Structural Dynamics and Materials Conference, Dallas, TX, 13-15 Apr. 1992; Sponsored in Part by AIAA, ASME, ASCE, AHS, and ASC

93. C. C. Chamis, P. L. N. Murthy, and L. Minnetyan, "Progressive Fracture of Polymer Matrix Composite Structures: A New Approach," NASA Report Number NAS 1.15:105574, E-6900, 22p, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH.(1992), also presented at the 14TH Annual Energy-Sources Technology Conference and Exhibition, Houston, TX, 26-29 Jan. 1992; Sponsored by ASME.

94. L. Minnetyan, P. L. N. Murthy, and C. C. Chamis, "Progression of Damage and Fracture in Composites under Dynamic Loading," NASA Report Number NAS 1.15:103118, E-5442, 17p, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH. (1990), also presented at the 31st Structures, Structural Dynamics, and Materials Conference, Long Beach, Ca, 2-4 Apr. 1990; Cosponsored by AIAA, ASME, ASCE, AHS.

95. L. Minnetyan, C. C. Chamis, and P. L. N. Murthy, "Structural Behavior of Composites with Progressive Fracture," NASA Report Number Report NAS 1.15:102370, E-5089, 19p, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, OH., January 1990.

96. Lindberg, H. E. (Ed.), "Failure Criteria and Analysis in Dynamic Response, American Society of Mechanical Engineers, Applied Mechanics Division, AMD," vol. 107, 40p, Published by ASME, New York, NY, USA(1990), proceeding of the Winter Annual Meeting of the American Society of Mechanical Engineers Dallas, TX, USA November 25-30, 1990.

97. B. O. Almroth, F. A. Brogan, "The Stags Computer Code," NASA Report Number NASA-CR-2950, 41p, NASA Contract Number NAS1-10843(Feb. 1978).

98. B. O. Almroth, F. A. Brogan, and M. B. Marlowe, ". Collapse Analysis for Shells of General Shape; Volume I. Analysis," Final Report. Apr. 69-Jan. 72, Air Force Contract Number F33615-69-C-1523, 1291p, Flight Dynamics Lab, Wright-Patterson AFB, OH, August 1972.

99. B. O. Almroth, F. A. Brogan, E. Meller, H. T. Petersen, and P. Stern, "Extensions to the STAGS Computer Code," Final Report October 1970-October 1972, Air Force Contract Number F33615-69-C-1523, 1275p, Flight Dynamics Lab, Wright- Patterson AFB, OH, March 1972.

100. B. O. Almroth, F. A. Brogan, E. Meller, F. Zele, and H. T. Petersen, "Collapse Analysis for Shells of General Shape: Volume II. User's Manual for the STAGS-A Computer Code, " Final Report April 1969-Oct 72, 12208p, Flight Dynamics Lab, Wright- Patterson AFB, OH, March 1973.

101. B. O. Almroth, Design of Composite Material Structures for Buckling - An Evaluation of the State-of-the-Art," Final Report. Jun. 1976-Oct 1980, 70p, Report Number LMSC-D681425, Air Force contract Number F33615-76-C-3105, Air Force Wright Aeronautical Laboratory, Wright- Patterson AFB, OH, (March 1981).

102. Robert S. Frankle, "Application of NDE Data to Finite Element Analysis of Parts Containing Defects," Proceedings of the International Symposium on Damage Detection and Quality Assurance in Composite Materials," San Antonio, TX, November 13-14, 1990, International Symposium on Damage Detection and Quality Assurance In Composite Materials, ASTM Special Technical Publication 1128, John E. Masters, ed., published by American Society for Testing and Materials, Philadelphia, PA, USA, (1992)

103. J. A. Nelson, "Nondestructive Data Application," Boeing Aerospace and Electronics, Report AL-TR-890071, Final Report to the Astronautics Laboratory(AFSC), Air Force Space Technology Center, Edwards, CA, August, 1991.

104. B, M. Lempiere, J. L. Cline, S. A. Gault, R. L. Partington, R. T. Huber, "IUS CT and Ultrasonic Scan Criteria Report," D290-11253-1 Rev A., The Boeing Company, Seattle, WA, September 1986.

105. R. A. Kline, G. Cruse, A G. Striz, E. I. Madaras, "Integrating NDE-Derived Engineering Properties With Finite element Analysis for Structural Composite Materials, Ultrasonics, vol., 31, no. 1, (1993), pages 53-59.